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A Mingled Yarn

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The behavior of nonliving and living systems is generally viewed as being qualitatively different. The key difference is often summarized by saying that whereas living systems are complex, nonliving ones are simple. This distinction is often the basis for claiming essential differences in conceptual stances, methods, and theories between scientific fields. I argue first that nonliving systems can display the unpredictable, irreducible, irreversible, and emergent—in sum, complex—properties of living systems. Then I discuss an emerging field called complexity theory, the principles of which offer the promise of bringing quantitative unity to an enormous range of phenomena, living or dead.

Key words: dynamical systems, complexity, nonlinearity, instability, feedback, irreversibility, emergence

The web of our life is of a mingled yarn, good and ill together: our virtues would be proud, if our faults whipped them not; and our crimes would despair, if they were not cherished by our virtues. (William Shakespeare, *All's Well That Ends Well,* IV, iii)

Radical behaviorism is a movement continually attempting two seemingly incompatible activities: defining itself to often hostile outsiders, and defining itself to often confused but committed insiders. To complicate matters further, the primary strategy for behaviorism's finding itself seems to be to search for its home among some group of putative nonintersecting conceptual sets—mechanism, contextualism, selectionism, molarism, or whateverism—in an apparent attempt to achieve status through simplification.

Why all this effort at conceptual botanizing? I see at least two reasons, one honorable, the other not. The latter is reflected in amplifying some perspective of behaviorism to conform to a more clearly dominant movement (i.e., cognitive psychology) for political reasons, as if the mouse might curry favor from the cat by exclaiming that both possess whiskers. Why should the cat care? Such an impudent mouse should and would be quickly swallowed up.

The intellectually honest efforts are devoted to characterizing behaviorism so as to encompass the complexity of behavior as we observe it. This is, in part, a reaction to what is seen as oversimplified accounts of behavioral phenomena emerging largely from the experimental behavioral analysis community. A key perspective of these categorizing efforts is that the model of physics as that science whose methods and both qualitative and quantitative approaches are most appropriate to the analysis of behavior is woefully inadequate, and that we should look to other sciences such as evolutionary biology as our model.

I should like first in the course of this essay to present this flee-from-physics argument, then to discuss why I believe it to be, if not flawed, then certainly narrowly based. In the course of this analysis I will try to provide some functional criteria for the term *complexity,* and sketch very briefly an emerging field known as *complexity theory,* which is providing some important quantitative insights into fields as seemingly diverse as physics, chemistry, evolutionary biology, embryology, genetics, ecology, economics, and international relations (e.g., Casti, 1994; Coveney & Highfield, 1995; Saperstein, 1995; Waldrop, 1992).

PHYSICS VERSUS BIOLOGY

Ernst Mayr has been a major figure in the history and philosophy of biol-

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TABLE 1

Physics versus biology/behavior

Universal	Particular
Essentialism	Variation
Determinism	Stochasticism
Reductionism	Emergence
Transformational evolution	Variational evolution
Temporal symmetry	Temporal asymmetry
Immediate causation	Historical causation
Functional relations	Functionalism
Simplicity	Complexity

ogy and has written extensively on the place of biology in the community of sciences. His arguments closely parallel those of many behaviorists in defining a special place for a science of behavior; indeed, he is often quoted by them. His contrasts of biology and physics, as exemplified in his essay "Is Biology an Autonomous Science?" (1988) and in his famous text *The Growth of Biological Thought* (1982), include virtually all the major criteria that various behaviorists (e.g., Baum, 1994; Chiesa, 1994; Donahoe & Palmer, 1994; Hayes, Hayes, & Reese, 1988; Morris, 1993; Reese, 1994; Zeiler, 1992) have espoused as distinguishing behaviorism or behavior analysis from something they call "mechanism," where the term *mechanism* to them means primarily the methods and general conceptual framework of physics. Table 1 is an adaptation of Mayr's criteria, including some seasoning from the behavioral literature.

Let me examine briefly and uncritically these criteria because (a) they set the stage of much of the succeeding discussion, and (b) the terms do not necessarily have obvious meanings. Also, some of these criteria may overlap or be imbedded in other criteria, as I will try to point out.

Universal Versus Particular

Laws or principles in physics are believed to apply without restrictions of time and space; physics would be the same in another galaxy as it is here on earth. For example, a fundamental postulate of relativity is that the laws of physics do not depend on the state of motion of an observer. Living beings, including their behavior, are generally viewed as exceptions in the universe, thus requiring restrictions in time and space. Individual differences are considerable; generalizations are relatively few; many exceptions are the rule. *Particular* is a term strongly related to *contextual.* At least some who call themselves contextualists uphold this distinction in the face of the alternative, mechanism.

Essentialism Versus Variation

In a somewhat similar contrast to the "universal versus particular" above, physical sciences are said to be based on a reductive perspective wherein composite structures are comprised of and understood on the basis of *fundamental particles* with unvarying properties. Biological systems, on the other hand, demonstrate considerable variation, with no agreed-upon fundamental units; indeed, variation fuels the engine of natural selection and thus evolution. Some behaviorists talk as if selectionism stands apart from mechanism (e.g., Baum, 1994; Donahoe & Palmer, 1994).

Deterministic Versus Stochastic

Classical physics is everyone's epitome of a deterministic predictive theory. Given initial conditions, Newton's laws, for example, can predict the motion of a body in space with extraordinary precision; enough, say, to send a Voyager spacecraft a billion miles to photograph Neptune. As the mathematician John Casti (1994) has pointed out, "the laws governing planetary motion are about the closest thing the human race has yet discovered to a sure thing" (p. 87). In contrast, biological and behavioral events may be very difficult or even impossible to predict. For example, from the perspective of the Cambrian period, it would have been impossible to predict the kinds of creatures roaming around in the Jurassic. At best, it appears, we must be content with a considerable role for chance in the affairs of man and beast.

Reductionism Versus Emergence

This distinction addresses the issue of whether phenomena at one level of observation are totally accountable by events taking place at a subadjacent level, or, whether novel or qualitatively different events can emerge unpredictably from any consideration of the reductive components. Another way of expressing this is to consider if a system is always analyzable or understandable in terms of the properties of its constituents.

Transformational Versus Variational Evolution

Physical systems are said to change largely through transformations involving internal, or what might be called constituent, mechanisms. This is contrasted with selective processes acting in conjunction with variants. Compare, for example, stellar evolution with organic evolution.

Temporal Symmetry Versus Temporal Asymmetry

Classical mechanics, as do relativity and quantum mechanics, reflect temporal symmetry. That is, changing the time t to $-t$ does not result in a different law. A raindrop accelerating toward earth does so under an attractive force $-F$. If that raindrop accelerated away from the earth, it would do so under a repulsive force $+F$ of equal magnitude but opposite direction. The law remains the same. Biological systems, including behavior, seem to manifest temporal asymmetry. For example, it would be unimaginable (although not absolutely impossible) for natural evolution to reverse itself along the exact same pathway to restore the dinosaurs to their original forms and numbers. Behavior analysis, too, is described as an historical science as opposed to the apparent ahistorical character of a mechanistic physics.

Immediate Versus Historic Causation

The traditional billiard-ball perspective of physics sees events at one moment completely determining, at least in principle, what happens the next moment, and so on. This idea implies a strict determinism. Biobehavioral systems, however, are said to demonstrate *historical causation,* whereby present events are typically determined by a history extending perhaps far back in time. Such systems can be said to have a *memory.* The overall distinction is strongly related to that between proximal versus distal causes, determinism versus chance, predictability versus unpredictability, or predictability versus interpretation. In the last contrast, we cannot predict some phenomena using an organized system of quantitative laws, but rather must be content with, at best, a coherent interpretation of the observed phenomena consistent with some encompassing theory. Typically, although not always, such a theory is qualitative, comprised of verbal constructs and concepts, as opposed to a mathematical structure. Modern cosmology is a notable exception.

Functional Relations Versus Functionalism

Zeiler (1992) expresses this distinction succinctly:

> Causation looks back in time to describe how the behavior is determined. Function looks forward to describe what the behavior accomplishes. . . . The ability to find clear cause-effect relations provides no perspective on whether or not the behavior is worth studying. . . . Accomplishment puts behavior and subsequent causal analyses in context. (pp. 417–418)

Simplicity Versus Complexity

This contrast represents either a source from which all the other distinctions flow, or, alternatively, a sink into which all the others flow to define complexity itself. I see the distinction as the sum of all the previous contrasts. Mayr, for example, continually emphasizes that biological systems are far more complex than any nonbiological system. Moreover, for him this means basic qualitative differences exist between the living and the nonliving, and thus there exists the necessity of an independent science of biology.

Because the listed criteria can serve to define complexity in our descriptions of nature, I should like to focus primarily on the last contrast to indicate how we might bridge the conceptual chasm between the quick and the dead.

BRIDGING THE CHASM

There are a number of questions occasioned by asserting that qualitatively distinct features arise from complexity. What is meant by complexity? Alternatively, what is meant by simplicity? If some agreement can be reached on the distinctions, then additional questions arise. How can complexity arise from simplicity? How can simplicity arise from complexity? The latter question could originate, for example, from consideration of Skinner's (1957) comment that Newton's law of gravitation may not be simple, but is far simpler than anything the layperson might say about the same thing.

From the outset, it seems clear that *simplicity* and *complexity* are not natural catagories, but are dependent on the interacting contingencies between the system of interest and the observer. As Wittgenstein (1968) emphasized in the *Philosophical Investigations,* the terms *simple* and *complex* (or *composite*) are relative to context. Here is his famous comment:

> Suppose that, instead of saying "Bring me the broom," you said, "Bring me the broomstick and the brush which is fitted onto it!"—Isn't the answer: "Do you want the broom? Why do you put it so oddly?" (p. 29)

Although we might all agree that context is an essential factor in defining complexity as opposed to simplicity, we cannot get very far with this if we are to treat the distinctions seriously. Essentially, we must address the conditions occasioning the use of such terms. No matter how complex we might consider a flea, all of us would likely agree that an elephant is somehow more complex. The task of making the ineffable effable involves not only a possible set of examples but also a general perspective in which to place the examples. As a beginning, we might view relativity of complexity, at least within the context of the distinctions sketched earlier, as implying a *quantitative* as opposed to a *qualitative* difference. Every contrast mentioned earlier to distinguish the science of physics from that of biology (and with it, behavior), I will assert, could be challenged not only in the abstract by appealing to a quantitative argument but also by example from constructed or natural systems.

Underlying the quantitative argument I want to advance resides a unifying approach: *dynamical systems theory* (e.g., Baker & Gollub, 1990; Guckenheimer & Holmes, 1986; Moon, 1992). The term *dynamical system* may be familiar to some as referring to chaotic dynamics. Although chaotic systems are dynamical in the sense I want to develop, they represent only a part of the field of dynamical systems.

Dynamical systems encompass a huge variety of phenomena ranging from mechanical, electrical, and chemical processes to computer programs to neural networks to the economic marketplace and to, yes, I will argue, biobehavioral phenomena. Some of the examples and applications are old, but many reflect very recent collaborative efforts among physicists, mathematicians, meteorologists, economists, biologists, engineers, physiologists, physicians, ecologists, chemists, computer scientists, and others who have come to talk of many things—of turbulence and taffy, of populations and planets, of pendula and percolation, of arrythmias and attractors, of clouds and coastlines and catastrophes, of stocks and spots and storms, of beams, basins, and bifurcations, of ferns, faucets, and fractals. Their goal is to generate what they call "reality rules" (e.g., Casti, 1992), that is, mathematical models of the everyday world—the booming and the buzzing confusion, the elegant and intricate patterns, the plain messiness, and, of course, the slings and arrows of outrageous fortune—all features of the biobehavioral domain. As I will point out, these kinds of models can display the stochastic, emergent, historical, selective, functional, and irreversible features that are supposed to characterize only living, evolving, behaving systems.

The point of all this is to bring together communalities of nature, bridging fields that have closely defended their domains by highlighting their putative conceptual and methodological differences.

Significant communalities do not imply identity. The theoretical physicist who is wrestling with a mathematical group categorizing system for elementary particles seems to be doing something different from the taxonomist who is deciding if a newly discovered creature belongs to a known species. Yet it could be argued that there are family resemblances to all instances labeled as *categorizing,* else what function does the term have?

THE MECHANICS OF COMPLEXITY: DYNAMICAL SYSTEMS THEORY

As Casti (1994) asserts, complexity is the mother of surprise. Surprise occurs when our models of nature are faulty. In our efforts to understand nature we make assumptions (e.g., linearity) that allow us to derive relatively easy conclusions about the past, present, and future states of the world. Although this sort of approach has taken us far along the road to apprehending some of the features of nature, we are only just beginning to see that we have been residing in a crystal palace of special, highly simplified cases. The world around us, the world we are really interested in as scientists, is full of surprises—in physics, chemistry, biology, and behavior. The sources of these surprises are many. My task is to show how some of these sources can provide conceptual bridges between the contrasting stances briefly introduced earlier. They include stochastic processes, chaotic behavior, instabilities (catastrophic or otherwise), noncomputable systems, irreducible systems, many-variable interactions, combinations of positive and negative feedback (with and without delays), emergence, and, of course, combinations and interactions of all of these. There will not be space here to discuss all of these possibilities, but only to look at a few cases as they bear on the distinctions raised earlier.

As mentioned before, the integrative perspective is dynamical systems theory. In its most abstract form a dynamical system consists of two components: a manifold and a vector field. The manifold is a space (sometimes called a phase space or a state space) in which motions or changes in the system are pictured. It is the playing field of the dynamical system. The vector field characterizes the motions within the manifold, that is, it specifies the rules of motion. A simple example is the motion of pendulum. Imagine a weight attached to a rigid rod suspended loosely by a nail. The weight is free to move 360 degrees in a plane. What are the properties of this system? How do we describe the possible states of motion? These are fundamental questions asked of any dynamical system. If the weight is displaced from its normal downward vertical position, it will swing back and forth with ever-decreasing displacement until it finally stops in the original downward position. It will remain there forever unless displaced again, in other words, subjected to some perturbation.

States of motion of a dynamical system (including rest) that are achieved after transients die out are called *attractors.* An attractor is a point or set of points in the manifold that may be fixed, periodic, aperiodic (described by a complex surface like a doughnut), stochastic, or, as in the case of a chaotic system, strange. A state of rest is a fixed point attractor and is represented by a fixed point in the phase space. If there were no friction to counterforce displacement, then the pendulum, once displaced, would swing back and forth forever. The attractor in this case is a limit cycle, defining periodic motion. The geometry in phase space would be a closed curve. It is possible to excite a pendulum arrangement to produce a *strange attractor*—instead of a simple closed curve, the path can wander around forever, never repeating or even intersecting itself—a mingled yarn. If one makes a slice (called a Poincaré section) through the phase space of this kind of attractor, one can watch on a computer screen as the tangled orbit cuts through the plane. Points accumulate in the time evolution of the chaotic system as they appear randomly in a bounded region like stars at dusk. Once a sufficient number has appeared, however, one can discern a wispy order with whorls and folds inside whorls and folds, and so on and so on—a section through the mingled yarn (see Figure 1).

Despite their name, strange attractors are far more common in nature than any another kind. Studies of strange attractors are part of a subfield of dynamical systems known as chaotic dynamics. Here we find a significant challenge to traditional perspectives on determinism, predictability, and chance, which has implications for some of the putative distinctions between physics and biobehavioral phenomena. Many dynamical systems have been modeled (in physics, population biology, meteorology, etc.) that yield strange and other kinds of attractors generally describing the data obtained through observation and experiment. I say "generally" because the correspondences can never be exact; unpredictability is inherent in the dynamics. The rules (actually, nonlinear differential or difference equations) are strictly deterministic (space does not allow me to discuss the very significant and difficult area of stochastic equations), but the application of those rules yields unpredictability; in other words, determinism and predictability are not equivalent. Thus, two important emphases here: (a) Deterministic models do not necessarily yield predictable outcomes, and (b) complex data do not necessarily require a complex model.

Thus, asserting that physics deals primarily in deterministic and therefore predictable systems, whereas in biobehavioral systems chance is the rule, is obviously simplistic. Chaotic dynamics has been useful for modeling systems in both fields; where strange attractors are involved, predictability is lost. The only way to know what will happen is to let it happen. This is actually another way to view complexity, namely that the complexity of a system is directly proportional to the shortest possible description of it. A random sequence of events means that the only way to describe it is simply to specify the sequence, in other words, there is no algorithm or rule shorter than the sequence itself. Rule governance finally meets contingency-controlled behavior.

A fundamental defining feature of chaotic systems is sensitivity to initial conditions. In linear systems a small change in initial conditions produces only linear effects in time. In nonlinear chaotic systems, the effects grow exponentially with time. This has implications for the limitations of measurement as well as the effects of perturbations to a system. If you have exactly the same initial conditions, the system will unfold in exactly the same way; this is simply another way of saying it is deterministic. But, of course, there is no way for this to happen. In the real world, precision is always limited and change always occurs. Thus, *determinism* in this case is not practi-

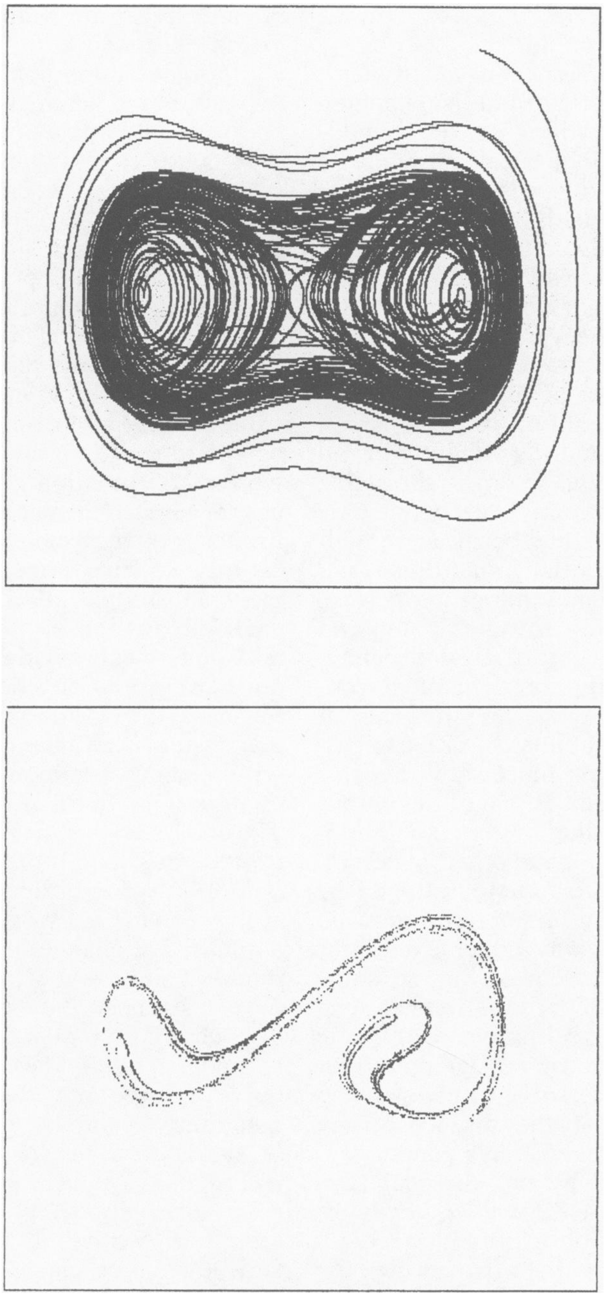

Figure 1. The top frame shows a phase portrait (velocity vs. position) of the motion of a member of a class of dynamical systems exemplified, for example, by the vibrations of a buckling beam under compression. The beam buckles to the right or left seemingly at random, but not really. This is a strange attractor. As the beam buckles to one side or the other, it shakes a bit, then after a while shifts to the other side, shakes a bit more, then shifts back again, and so forth. It is impossible to predict how much it will shake in place, or when it will shift to the other side. The bottom frame shows a Poincaré section, cut through the middle of the frame above, from right to left. This is another strange attractor, actually a fractal. As a fractal, it would show structure at any magnification. Practically, of course, only a finite number of points can be displayed, in this case about 10,000.

cally different from *random*. Figure 2 illustrates an example.

A fundamental aspect to any dynamical system, chaotic or not, is its degree of stability. Returning to our pendulum, the fixed point attractor with the weight hanging down is clearly stable. If locally disturbed in any way, the weight will eventually return to that point. Imagine, however, very carefully moving the weight upward to its maximal point on the vertical so that it is just balanced at the top. This point is an unstable fixed point, actually a *repellor*. Any deviation, however small, from this point and the weight will fall away, eventually to return to the stable point at the bottom. Clearly, chaotic systems are unstable because of their sensitivity to initial conditions and their nonperiodic, random properties. Biochemical, physiological, genetic, embryological, ecological, and behavioral systems all are dynamical processes that show varying degrees of stability and instability. In order to persist, such systems must show at least local stability; that is, small deviations do not disrupt the system so that it wanders off to some other state, including ceasing to function altogether.

Our hearts beat on hour after hour in a quasi-periodic way under conditions of our rest and of our racing. At some point, however, a perturbation can lead to ventricular fibrillation, a chaotic state with an often fatal outcome. Our lives may thus dissolve in chaos.

A population in the absence of any outside influences displays genetic stability, expressed by the classical Hardy-Weinberg law. However, an interactive combination of mutation, selection, migration, disturbances in the ecology, and random genetic drift may lead to completely new species and the disappearance of the old.

The dynamical systems we behavior analysts study in the laboratory, controlled by contingencies of antecedents and consequences, show varying degrees of stability. Small ratio schedules engender an almost periodic two-state performance. If we increase the ratio beyond a certain value, the behavior becomes more and more unstable while maintaining some of its original two-state character. Ultimately, only one state prevails—not responding.

A major concept that describes how systems respond to changes in conditions is *bifurcation*. The most famous example is found in May's logistic equation describing population dynamics. When the parameter specifying rate of fecundity of a generation is increased, at first the population increases monotonically. Then at some critical value of the parameter, the population begins to cycle up and down, in other words, a bifurcation in population values occurs. Increasing the parameter further produces more and more bifurcations so the population takes on more and more values. Eventually, all chaos breaks loose; the population can take on any value within a range. Without getting into any deeper technicalities here, the main point is that dynamical systems can take on new character with changes (sometimes very small changes) in controlling parameters. The most striking cases display catastrophes. Just one more person walking onto a crowded bridge may cause it to collapse. This is by common judgment a qualitative change in the system; one minute you have a bridge, the next you have a disaster. Nevertheless, there is an overarching quantitative approach to understanding the system; a qualitative change is predictable from a quantitative model.

This raises the tricky problem of *emergence*. We have already seem that even relatively simple nonliving systems can behave in surprising ways. But emergence carries an explicit antireductionist flavor to it. Something appears to be unpredictable from known properties of its constituents. But this too is an old story in the physical sciences. To begin with a simple example, temperature is a molar property of matter; it can be said to emerge from the statistical mechanics of zillions of atoms and molecules. The old cliche about not understanding any-

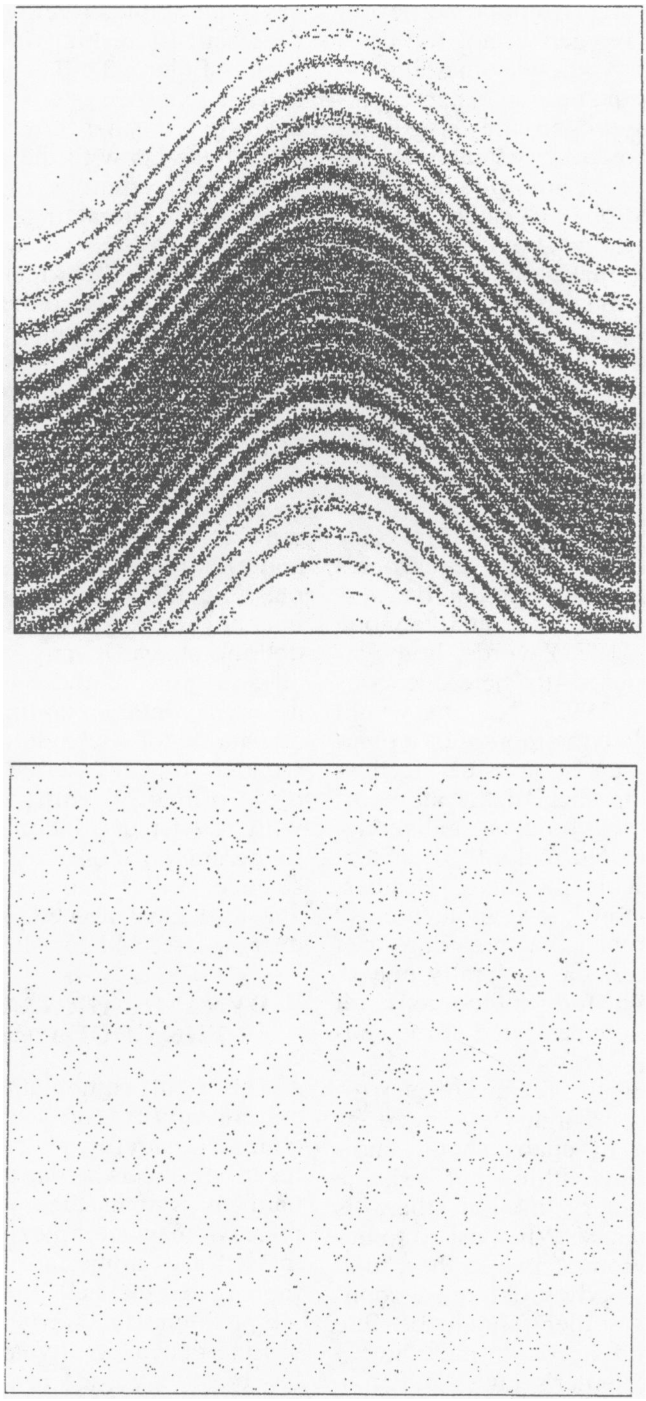

Figure 2. The top frame shows a phase portrait (velocity vs. time) of the motion of a bouncing ball on a vibrating table. Think of a ping-pong ball sitting on a table during an earthquake. The bottom frame is a portion of the top magnified to show stochastic motion. The points are distributed randomly. A deterministic model produces random behavior.

thing about water from properties of hydrogen and oxygen is not the case. It is possible to know something by calculating the quantum mechanical interactions of hydrogen and oxygen. In most cases, however, calculations of properties of matter are limited by their complexity. No one has calculated that sodium and chlorine should form a cubic structure to make salt, or has been able to predict the tertiary structure of proteins from their sequence of amino acids.

Still more interesting, and pertinent to making strong distinctions between studies of the living and the nonliving, is the old problem in mechanics known as the *N*-body system. I said earlier that the classical mechanics of planetary motion is the epitome of everyone's idea of a deterministic, reductive system. From the start, its reductive mode is, in Nagel's (1979) words, homogeneous, as opposed to heterogeneous (see also Marr, 1992). No one would or could calculate the motion of a planet around the sun by considering how gravity acted on each of the atoms of the planet! That would be real reductionism, and would make the problem infinitely difficult to solve. Besides, what did Newton know about atoms? In fact, he showed that breaking up a body into pieces was generally unnecessary; just treat the problem as if all the mass were concentrated at the center.

The deterministic feature of Newtonian mechanics is highly overrated, as the discussion of chaos should indicate. But even within that pristine world of planetary motion, there is complexity aplenty. When asked to describe the motion of the earth around the sun (a two-body problem), a sophomore physics student should be able to give a good account, including a derivation of Kepler's laws. But give this student a problem with three identical bodies interacting gravitationally, and neither she nor anyone else knows how to calculate how this system will move. Numerical simulations under the special condition that one of the bodies has a negligible effect on the other two show an astonishing mingled yarn of orbits (Figure 3). The essential difficulty is that the system cannot be taken apart to consider how each separate body interacts with the other two. In a word, the system is irreducible. Systems with interacting variables may display surprises that are not predictable by taking the effects of each variable into account and then adding them up. This is simply another way of saying that the system is nonlinear.

Behavior can be full of surprises because it is virtually always the outcome of many interacting variables. Consider the initial conditions we label as motivational variables. These modify the reinforcing, punishing, discriminative, and eliciting effects of stimuli. Examples include deprivation, stimulation, history, context, and various neuroendocrine states. In any given situation, all and more of these classes of variables may interact nonlinearly to set up a pattern of behavioral events. No wonder Mayr asserted that biology deals primarily with particular events with restricted principles, as opposed to the universal ones in physics. But all science deals with particular events, and as I have argued, surprises occur everywhere, and for similar reasons.

DYNAMIC ORGANIZATION: THE EDGE OF CHAOS

The right combination of stability and instability can lead to new and complex patterns of dynamical organization. This is a central dogma of dynamical systems theory as it attempts to encompass complexity. Living systems, for example, are said to sit "on the edge of chaos," a phrase I will attempt to clarify shortly.

Emergence in dynamical systems has been expressed in recent times by the unfortunate phrase "self-organization." Through a combination of positive and negative feedback, nonlinearities, and interacting variables, patterns of organization can emerge that are not clearly the outcome of any one con-

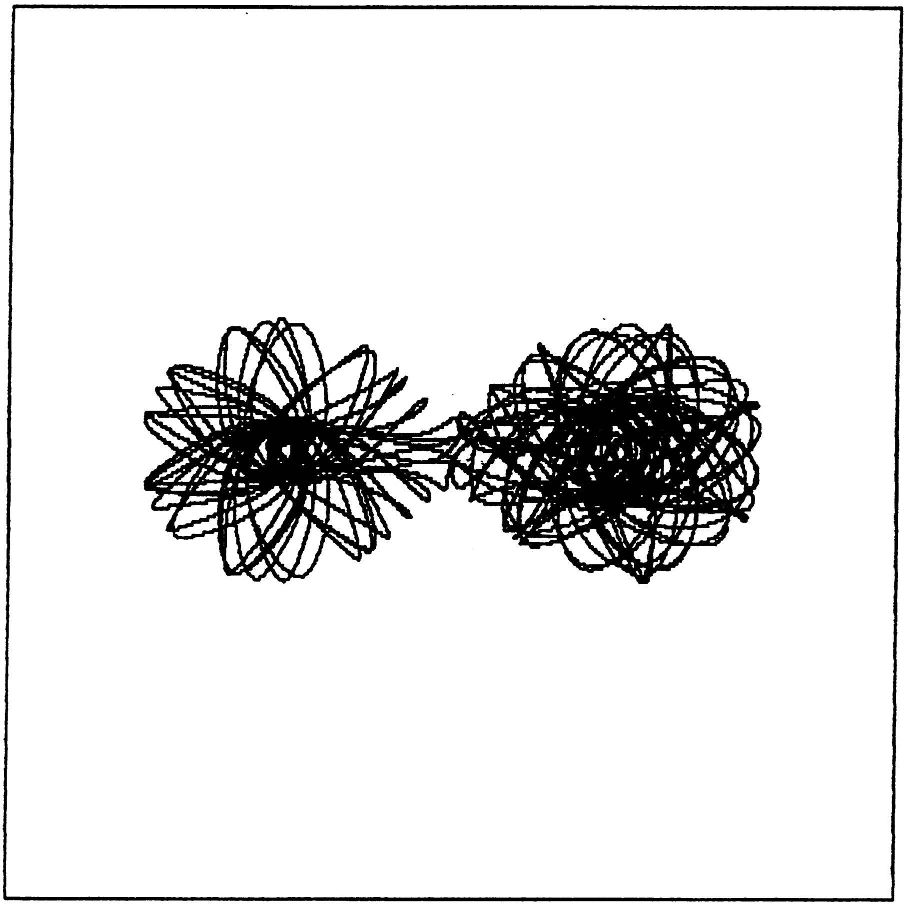

Figure 3. A simplified but irreducible three-body system. This is how, say, an earth-sized planet might orbit a double-sun system. The planet wanders aimlessly around one star, then, unpredictably, moves over to wander aimlessly about the other. Imagine trying to figure out what year it is! Actually systems of this kind are likely to be unstable. The little planet would eventually be slingshot out into endless space.

stituent or an additive combination of them. Phase transitions in thermodynamics provide many examples. Consider water on a winter day freezing on the outside surface of a window. The change from the essentially random arrangement of water molecules in a liquid drop to the beautiful crisscross, brushy, tree-like structures sweeping across the glass is not a property predictable from individual water molecules. What we view with awe is the dynamical organization of perhaps 10^{20} or more molecules. Such phenomena are ubiquitous in nature—in fluid flow, convection, crystals, hurricanes, tornados, sand dunes, galactic whorls, shapes of trees and leaves and flowers, proteins and DNA and viruses, and pigeons, possums, and people.

Our understanding of the development of these kinds of structures is minimal; for the most part what understanding we have comes from systematic observations, doing experiments, and building mathematical or other theoretical models.

We have already looked at nonlinear systems with interacting variables. To look deeper into the dynamics of organization we need to consider feedback processes. Here the state, or out-put, of the system feeds back to modify the system. Negative feedback contributes to stability; deviations from some state provide forces that tend to return the system to its original state. Regions of the manifold where, despite perturbations, the system returns to an attractor are called basins of attraction. Thus, there is a direct relation between the concept of a stable attractor and negative feedback processes.

Whereas negative feedback contributes to stability, positive feedback leads to change. The proper combination of the two leads to dynamic patterning. The neuron is a system whose resting potential resists change until the change is great enough to produce a positive feedback relation between the membrane potential and the permeability of the cell to sodium. The inflow of sodium in turn reduces the membrane potential which leads to more sodium influx, and so on, and BANG, an action potential occurs. Once this happens, a refractory period follows, during which membrane mechanisms restore the resting potential of the cell through negative feedback processes.

The interplay of positive and negative feedback can result in remarkable dynamical patterns in chemical reactions (see, e.g., Murray, 1993). For example, autocatalytic systems of chemical reactions, wherein the products of reactions catalyze further reactions in a kind of cycle, can produce in the reactant vessel moving waves and spirals of extraordinary beauty. Autocatalytic processes combined with diffusion mechanisms appear to be responsible for colorations and other morphogenic features of organisms. Thus, the leopard gets its spots from chemical dynamics. Biochemical pathways in the body have complex dynamics of many sorts and are essential to the integrity of living processes. Autocatalyic reactions are thought by some to have been an important step in the origin of living systems.

In the operant conditioning laboratory, we see the development and maintenance of complex patterns of responding under various contingencies of reinforcement. How do these patterns emerge? There is discernible structure at several levels of analysis from sequences of interresponse times to interreinforcement intervals to overall day-to-day patterns and beyond. The effect of reinforcement is to induce change through selection. Reinforcement effects depend on the initial states of the system, for example, where in time, or what features of responding are occurring. As this continues, the system is changing, so reinforcement acts on a different pattern, and so on. The emerging patterns of behavior and the pattern of reinforcement delivery are in a kind of dynamic dance, a flowing partnership between the effects of patterns of reinforcement on patterns of responding and the countereffects of patterns of responding on the patterns of reinforcement. Together they typically produce some metastable pattern we might identify with a particular schedule (e.g., fixed interval, variable ratio, etc.). (For some examples of dynamical perspectives on behavior, see the special issue of the *Journal of the Experimental Analysis of Behavior* on behavior dynamics, May 1992.)

The concept of feedback function in the description of operant contingencies is a great advance. These functions generalize the concept of contingency and allow us to explore a whole new world of behavior–consequence relations. Recently, Jack McDowell at Emory University has begun this work on a theoretical level; it promises to take the field of contingency description and analysis into the 21st century.

As mentioned earlier, living systems are said to sit at the edge of chaos. Although there are important exceptions, living processes would not function effectively, with the proper responsive dynamic patterns, if they remained in a chaotic state. Yet, as we have seen, the combinations of nonlinearity, positive and negative feedback, interaction, dissipation, and irreversibility are the ingredients of recipes for complex patterns, including chaos. Those complex patterns of both living and nonliving systems so common in nature can be but short steps away from two extremes—the static, bland, or boringly regular world of the simple on the one hand; or, on the other, the wild, unstable, and potentially risky world of the stochastic.

THE ARROW OF TIME

The analysis of feedback leads naturally to the problem of immediate versus historical causation. There are actually two issues here. The first concerns at what point or points in time can events exert their effects on a system. The second and much more complicated issue is temporal symmetry or asymmetry, that is, what conditions might lead to a "memory."

Delayed feedback has been the subject of dynamical systems theory for some time. But there is a major developing (and very complex) field in applied mathematics that is investigating delay differential and difference equations. These have applications in many fields, including the analysis of growth of populations and the spread of epidemics. Delay of consequences can produce vexing and complex effects, as everyone knows, and delay models confirm this. However simple or complex delay effects might be, the difference between the immediate and the historical is a parameter difference, not a conceptual one. How much of a delay of effect is needed to make it historical? A great deal of nonsense has been written about taste aversion, for example, asserting that such an effect should overthrow all our ideas about conditioning, as if we already had some law requiring the interstimulus interval to be less than some particular value.

The more interesting issue is temporal asymmetry. This deliciously deep and controversial topic is one of the most vexing in all of science, and despite many years of argument, there seems to be no clear consensus (see, e.g., Coveney & Highfield, 1990). Without getting into all the details, irreversibility is an inherent part of complex systems, many of which, however, cannot be said to have a memory. But I do not think it is necessary to go further into the deep relations among probability, temporal symmetry breaking, and dynamics. We can approach the problem with a few simple examples. If we magnetize an iron bar by placing it into a current-carrying coil, we can demonstrate that particular history at any time subsequently. We have given the bar a history. We can even show a hysteresis effect. If we reverse the current and thus the magnetic orientation, the course of change in magnetism will follow a different function than the original. The history manifests an irreversibility. Hysteresis effects show up in many other dynamical situations as well, including those investigated via catastrophe theory (see, e.g., Coveney & Highfield, 1995).

Staddon (1993) and Killeen (1981) have explored quantitative models of behavior change that incorporate histories; that is, present behavior is not simply under control of the immediate context, but a cumulative history of response–consequence events. What is more, equivalent behaviors could have resulted from different histories. Staddon (1993) emphasized how this differs from classical Newtonian mechanics, under which, given the initial conditions, the system's future was assured. We have already seen that for many everyday systems to which one can apply Newton's laws, the future is unknown. The physicist has to wait like everybody else. What is more, a cumulative effects model like Staddon's transforms initial conditions into dynamic variables feeding back into the system—a recipe for complexity if there ever was one.

THE FUNCTION OF A FUNCTIONAL RELATION

As mentioned at the beginning of this essay, Zeiler (1992) has taken behavior analysts to task for emphasizing the search and generation of functional relations in idealized laboratory situations over the issue of what functions behavior may serve. An essential issue here is what kinds of behavior should we be studying, and in what ways. In other words, what is important, and how do we know? There are obviously no simple answers to such questions; they arise in every science, and history changes the answers. One could argue that sciences generally develop through first tackling the simple with simple methods, then advance to the complex. We could not have had dynamical systems theory and practice without Galileo and Newton. Yet such an argument is too facile. For one thing, in the case of dynamical systems, the same or similar principles apply to both the simple and the complex. Has traditional behavior analysis given us some basic principles to apply to the kinds of behavior Zeiler says we should be investing our time in?

In making his argument, Zeiler (1992) points to his results that the effect of certain contingencies can depend upon whether subjects are exposed to open or closed economies. This is an important finding to be sure, especially if it has wide generality. His interpretation of these results pins on issues of what behavior accomplishes, a form of explanation not common to behavior analysts. Answers to what gets accomplished call for some underlying theory, like optimality or melioration or satisficing or whatever. But these are constraints on a dynamical system. They are similar to principles of least action, or conservation of energy, or the second law of thermodynamics. Thus, in asking, for example, whether some class of behavior is optimal under certain initial and boundary conditions, we are applying a theoretical, quantitative dynamical constraint in the same way a physicist might invoke Fermat's principle that light always travels along the path of least time between points.

It is appropriate to finish this discussion with Mayr's treatment of the sort of behavior I think Zeiler (1992) is talking about, namely goal-directed behavior. Mayr (1988) calls goal-directed processes "perhaps the most characteristic feature of the world of living organisms" (p. 45). He is very careful to avoid the absurdities of teleology. He calls goal-seeking behavior "teleonomic." Teleonomic behavior is defined as a "process or behavior . . . which owes its goal-directedness to the operation of a program" (p. 45). A program in turn is defined as "coded or prearranged information that controls a process (or behavior) leading it toward a given end" (p. 49). He adds, "My definition of a program is deliberately chosen in such a way as to avoid drawing a line between seemingly 'purposive' behavior in organisms and in man-made machines" (p. 49). I have already alluded to the mathematical equivalence of a program and a dynamical system. So Mayr takes us full circle.

CODA

The one endeavor that binds all sciences together is the search for and understanding of *patterns* in nature—the movements of the spheres, the flow and turbulence of a stream, the shape of a snowflake, the branching of a tree, the crinkliness of a coastline, the spots on a leopard, and the course of true love. I have tried in this mingled yarn to suggest that the dynamical systems approach to complexity provides not only a means to understand the development of patterns of many kinds, but in doing so, also provides a bridge between seemingly very different, if not seemingly antagonistic, conceptual perspectives. Casti ends his book on complexity with a quote from the novelist Yourcenar that I cannot resist repeating here:

> The rules of the game: learn everything, read everything, inquire into everything. . . . When two texts, or two assertions, or perhaps two ideas, are in contradiction, be ready to reconcile them rather than cancel one by the other; regard them as two different facets, or two successive

stages, of the same reality, a reality convincingly human just because it is complex. (1994, p. 278)

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